

Development of an Acoustic Energy Density Probe Calibrator

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Abstract

An acoustic energy density probe is a sensor that uses multiple pressure transducers to measure acoustic energy density. Calibrating each pressure transducer an acoustic energy density probe at the same time is a difficult problem because the pressure transducers have a unique location and orientation. Two main issues arise that are involved in simultaneous calibration. The first issue is a uniform pressure issue. It arises from subjecting each microphone on the probe to the same known source at the same time because pressure is a function of distance and direction. The second issue is a seal issue. It arises from the probe/calibrator interface which must be sealed the same each time at each probe microphone.

The probe of interest for this research is spherically shaped with four pressure transducers mounted in the sphere. A shaft used to connect the sphere to DSP hardware and house the transducer wires is mounted in the sphere. The axis of this shaft is the natural axis of the sphere. One microphone is mounted on the opposite side of the sphere as the shaft, and shares the same axis as the shaft. This microphone is known as the pole microphone. The other three transducers are located 68.75° off the axis of the probe shaft as measured from the pole microphone. These three side microphones are spaced equally around the sphere at

120° increments. All four microphones are oriented tangent to the surface of the sphere at their locations. The unique microphone locations are the source of the probe/calibrator interface issues. These probes were designed to be direction-independent. This means that the orientation of the probe relative to the direction of the sound field does not affect the probe's ability to accurately measure acoustic energy density. In order for the probe to accurately measure acoustic energy density and be direction independent, each microphone must be accurately calibrated.

Introduction

Total acoustic energy density is the sum of the acoustic potential energy and the acoustic kinetic energy as shown in Eq. 1¹.

$$w_{Total} = w_p + w_k \quad (1)$$

In Eq. 1 w_{Total} is the total acoustic energy density, w_p is the acoustic potential energy, and w_k is the acoustic kinetic energy. Conceptually, the potential energy component is the pressure the sound produces at a certain location, and the kinetic energy component is the particle velocity of the sound field. The probes relevant to this research compute energy

density using pressure transducers. The potential energy is calculated directly from the pressure measurements produced by the transducers as shown by Eq. 2.

$$w_p = \frac{1}{2\rho_o c^2} p^2 \quad (2)$$

In Eq. 2 ρ_o is the ambient fluid density, c is the acoustic phase speed, and p is the acoustic pressure. The particle velocity is calculated using the pressure difference between two of the microphones. This technique is referred to as the two-microphone technique and can be expressed as shown by Eq. 3. Where u is the acoustic particle velocity, p_1 and p_2 are the pressure at the two microphones, ω is frequency of oscillation, Δx is the distance between the two microphones, and j is the square root of -1²³.

$$u \approx \frac{p_1 - p_2}{j\omega \rho_o \Delta x} \quad (3)$$

Since the particle velocity of the sound is directional, the two microphones used to get this pressure difference are chosen based on the direction of the sound. It is worth noting that in this case a particle refers to a group of air molecules that are moving in the same direction at the same speed and not the individual molecules of the median. Also worth noting is that particle velocity is produced only by the sound and not Brownian motion⁷. The acoustic kinetic energy is calculated using this particle velocity as shown in Eq. 4.

$$w_k = \frac{\rho_o}{2} u^2 \quad (4)$$

The probes of interest use four electret microphones. Electret refers to the dielectric material used in the microphones. Electret microphones are considered the best value omnidirectional microphones and are used in a wide variety of applications. Their low cost is a result of mass productions. Typically

electret microphones do not have an ultra-flat frequency response nor do they have long-term stability. Therefore, electret microphones need to be calibrated often at each frequency in the range they will operate.

Calibration is the process of comparing the output value produced by a measuring device to a known or desired output. Typically the device being calibrated is subject to a known input value or measurement standard. This comparison will yield a correction or calibration factor that when applied to the output results, scales the results to match the known output, allowing for calibrated measurements.⁴

Currently two calibration techniques exist. In the first technique, each microphone on the probe is calibrated individually.² This technique has the potential to introduce large errors in calibration. This is because the microphones are extremely sensitive to small changes in pressure. Therefore the seal around each microphone during each calibration must be the same. Forming a seal at each microphone calibration proves difficult to repeat. Calibrating all microphones on the probe simultaneously eliminates differences in the seal between microphones.

The second calibration technique is based on a lumped parameter model, which is based on the assumption that when distances are small compared to wavelength, pressure changes are minimal. This technique involves a calibration chamber that encloses the entire probe. The lumped parameter model is valid as long as $ka \ll 1$. Where a is the largest chamber dimension and k is the acoustic wave number. This means the largest chamber dimension needs to be much less than the size of the acoustic wavelength of the frequency used to calibrate⁵. If the

lumped parameter model is valid the acoustic pressure in the chamber is uniform. With a uniform pressure surrounding the probe, each microphone could be calibrated simultaneously. This technique is hindered, however, by the physical limitations on the size of the cavity due to the size of the spherical probe. This size constraint limits the frequencies at which the calibrator can operate, limiting the frequencies at which the probe can measure accurately.

The potential error associated with the first technique and the frequency limitations inherent to the second technique are the motivation for this research. Both of these techniques have been implemented in an attempt to calibrate the probe of interest in this research. The first technique was difficult to test since each microphone was calibrated separately. Calibrating this way caused a different seal to be formed at each microphone introducing error in the results. The second technique resulted in valid calibration results at low frequencies (less than 250 Hz). However, for frequencies greater than 250 Hz, the error in calibration between the microphones was greater than the objective of ± 0.5 dB re 20 μ Pa. Since the probe is equipped with electret microphones, the valid frequency range for probe measurements would only go up to 250 Hz. The probe is designed to be used up to 2000 Hz; and needs to be calibrated over this entire range.

Design

The concept developed was derived from an equivalent circuit model shown in Figure 1. Where U is the volume velocity (m^3/s), C_A is the acoustic compliance (m^5/N), and M_A is the acoustic mass (kg/m^4). This model conceived an

individual sound path for each of the microphones. In theory, if each of these paths is identical, has the same termination impedance, and originates from the same source, they will each see the same acoustic pressure at the end. This solution would be completely independent of the wavelength-dimension interaction.

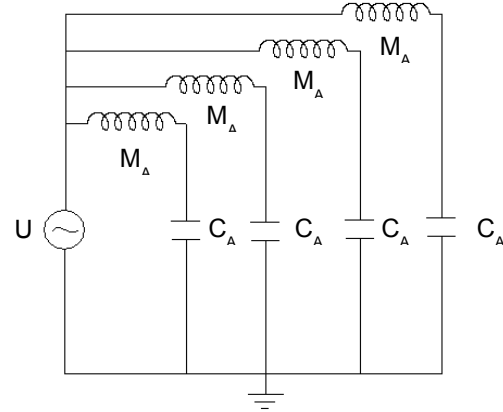


Figure 1: Equivalent Circuit Model

To verify the concept that the same pressure could exist at the end of each path, a driver was attached to a small piece of acrylic with five holes located symmetrically about the axis of the speaker. (See Figure 2) Four ports were included for the four microphones on the probe. The fifth port was included for the reference microphone.

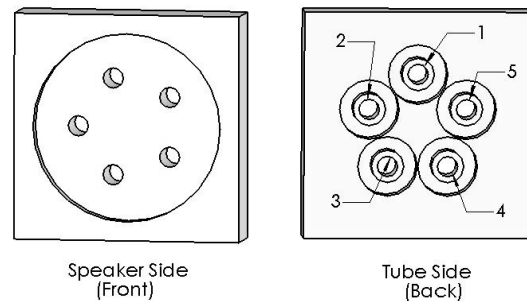


Figure 2: Five port driver attachment

The pressure was measured at each of the five ports shown in Figure 1, and averaged over five measurements at each frequency, from 500 Hz to 6 kHz. The maximum difference between any two holes was plotted as a function of frequency and is shown in Figure 3. The results looked promising below the cutoff frequency of the first cross mode (the mode across the diameter of the driver) which is 4.5 kHz.

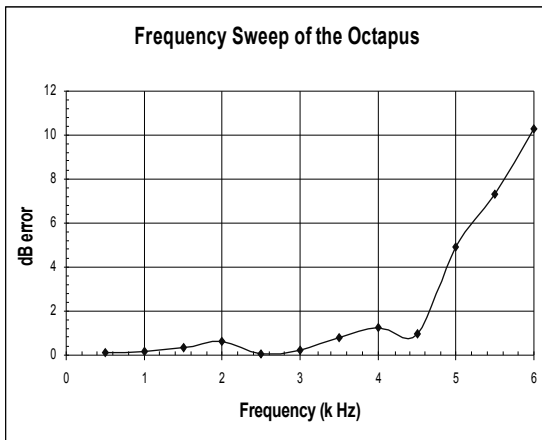


Figure 3

Since the error near 4 kHz was significant it was determined that the cross mode was affecting the error. To attenuate the cross modes, a plane wave tube was attached to the speaker extending the five ports shown in Figure 2 away from the driver. The length of the plane wave tube was calculated to be about 14 cm. This length corresponds with the cross mode being attenuated 90 dB, leaving only plane waves, which are uniform across the cross-section of the tube. The same test to produce Figure 3 was conducted and the results are in Figure 4. The error was decreased at 2 kHz. The error was minimal up to 3 kHz.

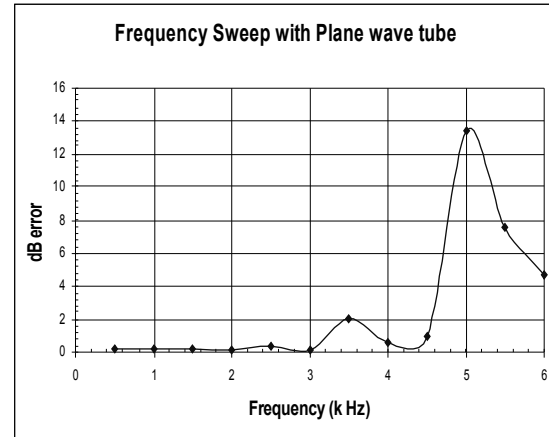


Figure 4

PVC tubes with an outside diameter of 15/32 of an inch were added to the end of each port. Since the microphones on the probe are 1/4 inch diameter, the tubes were chosen to have an inside diameter of 1/4 inch. (See Figure 5)

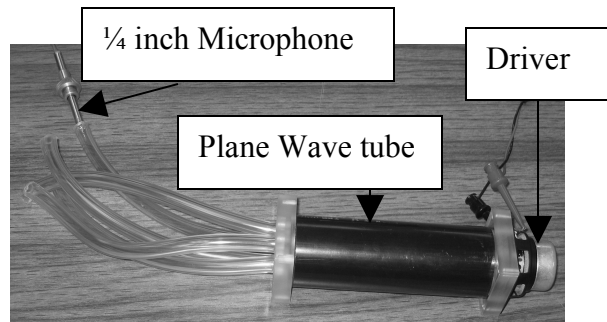


Figure 5: PVC Tube Test Set-Up

These tubes were tested using frequencies of 250 Hz, 300 Hz, 400 Hz, 500 Hz, 600 Hz, 700 Hz, 800 Hz, 900 Hz, 1000 Hz, 1500 Hz, and 2000 Hz. This upper limit was chosen based on the operational limit of the probe. The dB error was then calculated and plotted at each of these frequencies. Figure 6 shows the results of this test.

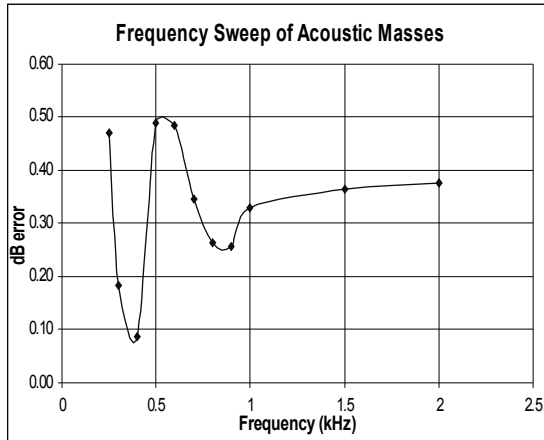


Figure 6

The goal was to get the error below 0.5 dB, and as can be seen from Figure 6 this was accomplished for the frequencies of interest of this probe.

Attachment Design

Attaching the tubes to the probe in the right place so as to line up with the microphones was next addressed. Since the microphones are not on the same side of the sphere, the tubes would need to be bent to reach all four microphones. This raised the question of how much error will be introduced as a result of bending the tubes. An experiment was conducted to measure this error. The pressure at the end of each tube was measured with the tube straight, and bent at 30, 60 and 90 degrees. The pressure was measured at each tube in each position five different times. An average was calculated at each orientation and an average of those was calculated. Using the overall average the error in dB was calculated to be 0.03 dB.

The tube attachment apparatus was designed using two halves with spherical cavities that come together and enclose the probe. The top half is equipped with a groove that allows the probe shaft to pass

through to its center. The bottom half, where the microphones on the probe are, is equipped with four ports. Each port is lined up with the microphones on the probe. Each port has a mic insert that is fit with an o-ring to seal the probe attachment interface. The mic insert is held in place by a bolt that has a hole in the center to allow the mic insert to pass through it. The bolts screw into the threaded holes of the attachment which line up with the microphones on the probe. (See Figure 7)

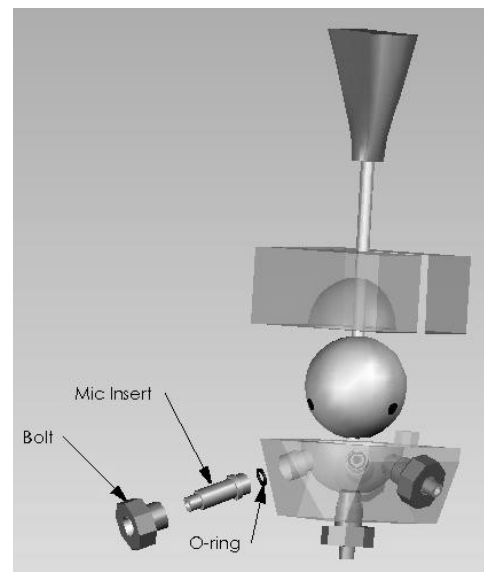


Figure 7: CAD Model of Attachment

The tubes which are attached to the driver via the five port attachment and plane wave tube shown in Figure 5 are attached to the mic insert. The two halves are held together with latches. Figure 8 is a photograph of the entire calibrator.

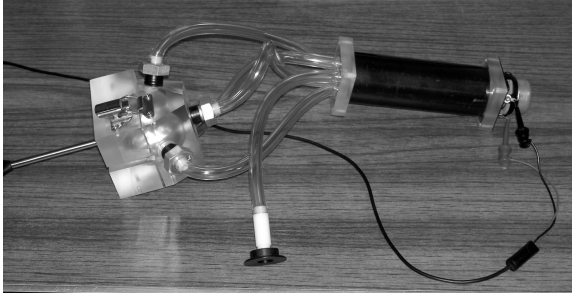


Figure 8: Attachment Test Set-Up

Figure 9 shows a close up of the probe, and the inside of the bottom attachment.

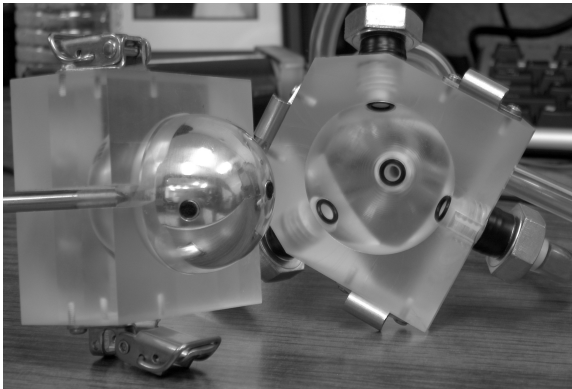


Figure 9: Probe-Attachment Interface

Results

The driver was excited with a sine wave having an amplitude of 114 dB. The probe was inserted into the attachment and a one second time signal was recorded for each microphone on the probe, and the reference microphone. The probe was taken out and rotated so that the three side microphones were at a different port. The pole microphone and the reference microphone remained in the same port. Another time signal was recorded and the rotation was repeated. This entire process was repeated for 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, and 3000 Hz. It is worth noting that physical limitations reduced the amplitude of the sine wave at 2 and 3

kHz. The results from the rotation tests were plotted by normalizing the data about the first position of each microphone. (See Figures 10-14).

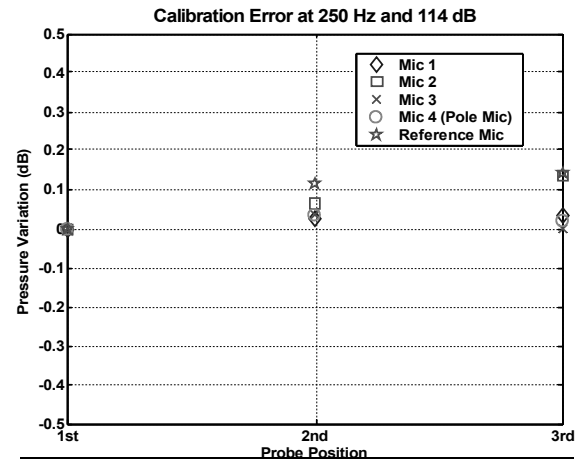


Figure 10: 250 Hz Results

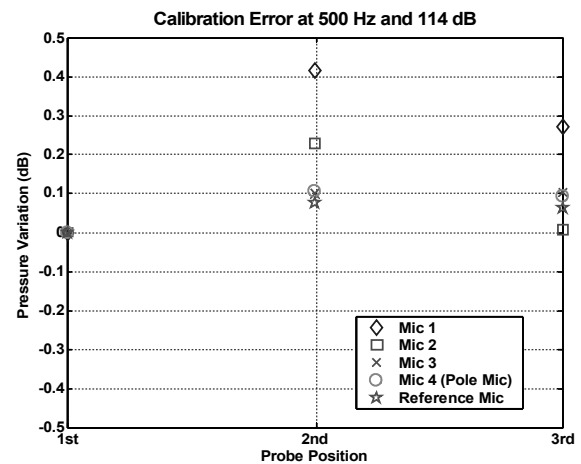


Figure 11: 500 Hz Results

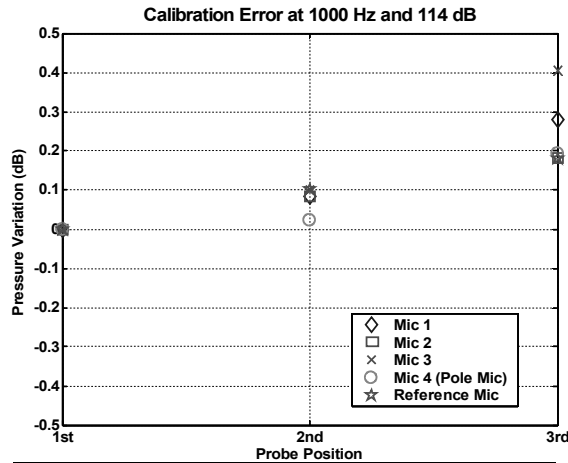


Figure 12: 1000 Hz Results

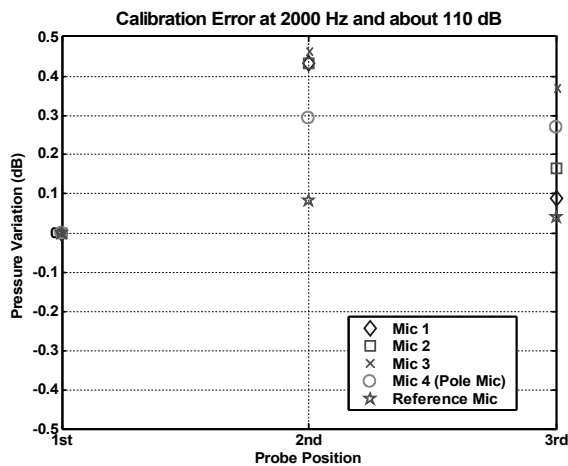


Figure 13: 2000 Hz Results (110 dB)

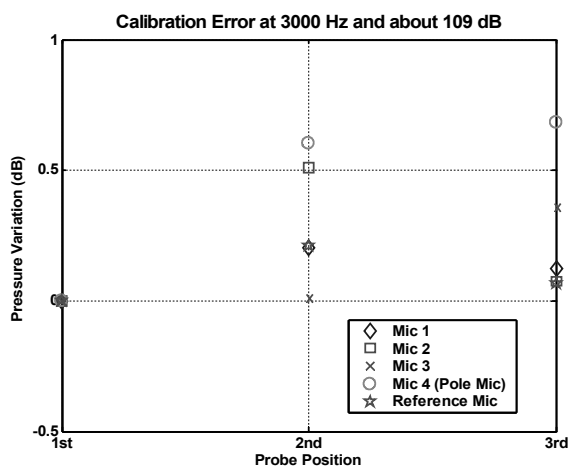


Figure 14: 3000 Hz Results (109 dB)

The error for the first 3 frequencies was far less than the 0.5dB target. At 2000 Hz the error was near the 0.5dB limit, and the error at 3000 Hz was above the 0.5 dB limit. The first 4 frequencies agree with the results in Figure 4 and Figure 6. Further investigation is needed to determine why the results at 3000 Hz do not agree with the results in Figure 4. This investigation would benefit calibration work for probes with operating frequencies above 2000 Hz.

References

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